Particle Acceleration and Sources in the November 1997 Solar Energetic Particle Events

G. M. Mason[1,2], C. M. S. Cohen[3], A. C. Cummings[3], J. R. Dwyer[1], R. E. Gold[4], S. M. Krimigis[4], R. A. Leske[3], J. E. Mazur[5], R. A. Mewaldt[3], E. Möbius[6], M. Popecki[6], E. C. Stone[3], T. T. von Rosenvinge[7], and M. E. Wiedenbeck[8]

[1] *Department of Physics, University of Maryland, College Park, MD*
[2] *Institute for Physical Science and Technology, University of Maryland*
[3] *California Institute of Technology, Pasadena, CA*
[4] *Johns Hopkins University / Applied Physics Laboratory, Laurel, MD*
[5] *The Aerospace Corporation, Los Angeles, CA*
[6] *University of New Hampshire, Durham, NH*
[7] *NASA / Goddard Space Flight Center, Greenbelt, MD*
[8] *Jet Propulsion Laboratory, Pasadena, CA*

Abstract

We report studies of two large solar energetic particle (SEP) events on Nov. 4 and 6, 1997 that were observed using advanced energetic particle detectors on the ACE and the Wind spacecraft. Both events showed enriched Fe/O, and had a ~1 MeV/n ^{3}He/^{4}He ratio = 2.1×10^{-3}, 4 times the coronal value. The Nov. 6 event had exceptionally hard spectra, with much higher intensities of high energy (10s of MeV) particles than the Nov. 4 event, yet below 1 MeV per nucleon the intensities in the Nov. 6 event were lower than for Nov. 4. Strong, complex temporal variations observed for ~120 keV Fe/O contrasted with only gradual changes of this ratio at ~25 MeV/n. A spectral break was observed in the Nov. 6 event, wherein below a few MeV/n the spectra became harder. Taken together, these observations point to different seed and acceleration mechanisms dominating at low and high energies in these events

1 Observations:

The energetic particle observations reported here were carried out with the Ultra Low Energy Isotope Spectrometer (ULEIS), the Solar Energetic Particle Ionic Charge Analyzer (SEPICA), and the Solar Isotope Spectrometer (SIS) on the ACE spacecraft, and the EPACT/STEP sensor on the Wind spacecraft (von Rosenvinge et al. 1995; Mason et al. 1998; Möbius et al. 1998; Stone et al. 1998). During the Nov. 4-11, 1997 period both spacecraft were well upstream of the Earth's magnetosphere (> 100 R_E). Figure 1 shows oxygen intensities from ACE with markers for other events during this interval. The first event was an X2/2B flare at S14W34° in active region 8100 beginning at 05:54 on Nov 4, 1997 (day 308 – from *Solar Geophysical Data, Part II*). The SOHO spacecraft observed a CME from this event, and the associated shock was observed by the ACE magnetic field and solar wind instruments at approximately 22:00 on Nov. 6 (day 310) followed by a magnetic cloud (Nov. 7 05:00 – Nov 8 12:00) detected on Wind. A second flare erupted at S18W63° from the same active region at 11:22 on Nov. 6; this event was an X9/2B event that produced ground level increases in neutron monitors (K. R. Pyle, *private communication*), strong gamma-ray emission of C, O, Ne, Mg, Si and Fe and neutron capture lines (M. Yoshimori, *private communication*), and a CME whose associated shock was detected by ACE at ~10:00 on Nov. 9 (day 313). Both events produced Type II radio bursts. Note from the Figure that the passage of the first shock, with the associated peak in low energy intensities, nearly coincided with the rise-phase of the Nov. 6 particle event. The first shock produced large intensity enhancements for low energy oxygen, with easily observable distortions of the time-intensity profiles up to ~2 MeV/n; at higher energies this shock passage did not produce large intensity increases, although such increases could have been masked in part by the rise phase of the day 310

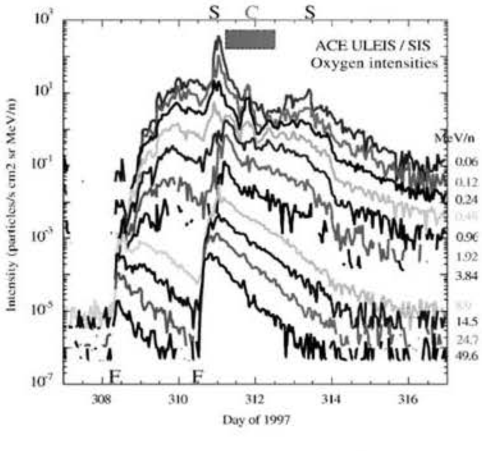

Figure 1: 1-hr average oxygen intensities from 60 keV/nucleon to 50 MeV/nucleon from ACE during the Nov. 1997 events; flare times are marked F; shock passages at ACE are marked S; the red box marked C shows the time of a magnetic cloud passage.

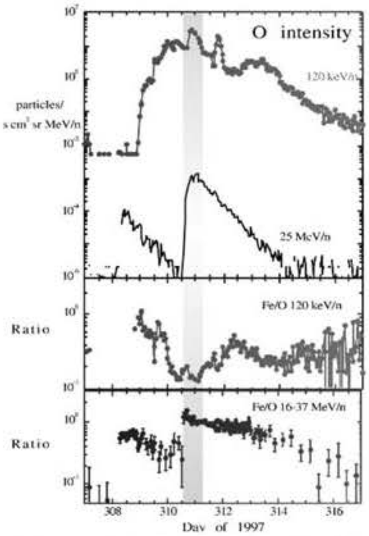

Figure 2: *Upper panel:* O intensities from ACE/SIS and Wind/EPACT at high and low energies. Yellow shaded area marks first shock passage. *Lower panels:* Fe/O ratio at 120 keV/n and 16-37 MeV/n.

event. The second ("weak") shock passage, on day 313, is associated with a slight increase in the lowest energy particle intensities (below ~500 keV/n).

The time-intensity profiles in Figure 1 show deviations from idealized smooth trends – while some of these features are due to statistical fluctuations, others are significant. This is explored further in Figure 2, which shows low and high energy oxygen intensities in the upper panel, and the ratio of Fe/O in the lower panels, with the shock passage on day 310 marked by yellow shading. At 120 keV/n the following features are seen in the Fe/O ratio: (1) an initial smooth decrease in the first SEP event, similar to that seen at the higher energy, followed by (2) a large (factor of 5) drop at about day 310.0, (3) little change during first shock passage, followed by (4) an increase around day 312.5 in coincidence with the arrival of particles from the second event. The striking (factor of ~5) decrease in 120 keV/n Fe/O near day 310.0 is caused by a drop in the Fe intensity while the O intensity continues to increase. After day 314, the fluctuations are statistical. In contrast, the 16-37 MeV/n Fe/O ratio shows simpler variations, decreasing by a factor of ~2 over the course of each event.

The average composition for major elements for the Nov. 6 event are similar over a very broad energy range from 150 keV/n to ~60 MeV/n (results for the Nov 4 event are similar). Compared to the average SEP value, Fe/O is enhanced by a factor of 3-4 at the lower energies, and by a factor of 8 for 12-60 MeV/n. Such ranges of Fe/O variation have been observed previously (Cook et al. 1984; Mazur et al. 1993; Reames 1995). Mazur et al. (1993) have shown that the event to event variations are generally smaller at low energies, as seen here. Figure 3 shows the 0.5-2.0 MeV/n ^{3}He/^{4}He ratio for the Nov 6 event. The observed ratio of $(2.1 \pm 0.08) \times 10^{-3}$ is the lowest finite value of this ratio ever reported; nevertheless it is a factor of 4 above the average solar wind value, and is below limits (usually ~10%) often used to identify ^{3}He-rich

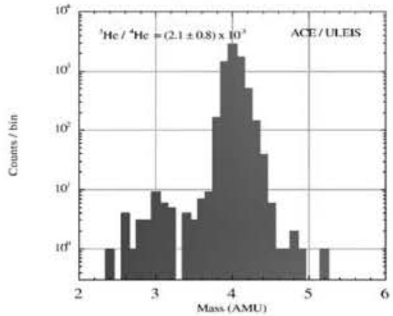

Figure 3: 0.5 - 2.0 MeV/nucleon helium mass histogram measured during day 312.25 through 314.0. Note use of a log scale.

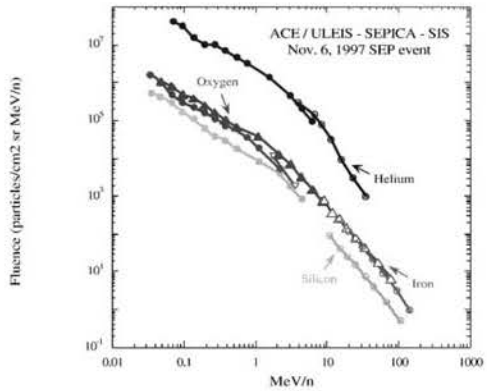

Figure 4: ACE fluences for the Nov. 6 event.: He points in blue; O points in green; Si in light blue; Fe in red. At high energies Fe and O spectra are nearly indistinguishable.

events. The ^{3}He/^{4}He ratio in the Nov. 4 event is similar. The arrival time of mass < 3.5 AMU events shown in Figure 4 was uniform, with 20 events detected on day 312 and 16 events on day 313.

Over the broad range of energies presented here, velocity dispersion causes significant differences in the duration of the event, increasing from 1-2 days at higher energies to the order of a week at low energies (see Figure 1). Under these circumstances, event-averaged particle intensities may be somewhat misleading since time periods of length suitable to capture the bulk of the low energy particles contain significant intervals where the high energy particles have decayed away. To explore spectral forms, we therefore show fluences for several elements in Figure 4. The time intervals used in Figure 4 were chosen at low energies to avoid the shock passage on day 310, while at high energies the entire event interval could be used since the shock did not produce significant numbers of high energy particles. At high energies, the O and Fe fluence spectrum is reasonably well represented by a power law in kinetic energy per nucleon with slope –2.1 (Cohen et al. 1999), while below ~1 MeV per nucleon it hardens significantly, with slope –1.1. The energy at which the spectral break occurs is difficult to identify precisely, but the data can be reasonably described as showing a break at 6-7 MeV/n for Helium, 2-3 MeV/n for O and Si, and ~1.5 MeV/n for Fe. Assuming typical SEP ionization states, this corresponds to a rigidity of ~200 MV. The Nov. 4 event also showed a roll over of the spectra at similar energies, but it was less pronounced.

2 Discussion:

Following previous work, and based on the radio emission and CMEs observed during this period, we interpret the low energy interplanetary particle population in these events as arising from acceleration at large scale shocks moving outward from the Sun. Although observations at 1 AU cannot uniquely separate the time duration of the particle injection from propagation time, we can roughly estimate upper limits of the duration of the injection by assuming that the major portion of the injection must be complete by the time of maximum intensity at 1 AU. The first 2 rows of Table 1 show such estimates for the Nov. 4 event using the curve fits to the data, along with an assumed linear propagation rate for the Nov. 4 shock, which arrived at Earth about 64 hours after the optical flare. The third row shows corresponding estimates for the Nov. 6 ground level neutron monitor response, which peaked approximately 2 hours after that flare. While these are admittedly crude estimates, they indicate that the lowest energy particles could have been acceler-

Table 1 --- Estimate of injection duration upper limits and corresponding shock travel

Energy	time to maximum	"direct" propagation time to 1 AU	Upper limit of injection time from flare	Upper limit of shock radial location at end of injection	
60 keV/n	50 hr	17 hr	33 hr	0.5 AU	100 R_S
8.9 MeV/n	8.2 hr	1.4 hr	6.8 hr	0.1 AU	23 R_S
relativistic	2 hr	<0.5 hr	~1.5 hr	0.025 AU	~5 R_S

ated by the shock out to sizable fractions of 1 AU, while for the higher energies the acceleration occurred within roughly 0.1 AU. Lockwood et al. (1990) have made comparable injection time estimates using 20 MeV-2 GeV protons, concluding that the injection time scaled as $1/\sqrt{E}$, while at high energies Kahler (1994) used 470 MeV to 4 GeV protons intensity observations to estimate CME injection heights of 5-15 solar radii (R_S).

A major feature is the difference in intensities in the two particle events: compared to the Nov. 4 event, the Nov. 6 event peak intensities are ~10 times *larger* at high energies, and ~5-10 times *smaller* at low energies. Clearly, the Nov. 6 event at the Sun was much bigger – and this difference is reflected in the peak intensities down to ~1-2 MeV/n. Since the high energy acceleration episode in the Nov. 6 event produced much higher intensities than Nov. 4, we presume that this was the case close to the Sun for low energy particles as well. However, at 1 AU passage, the interplanetary shock for the Nov. 6 event was smaller and produced only moderate intensity increases at low energies. The difference in high vs. low energy intensities is presumably due to the fact that at low energies the particles observed at 1 AU are dominated by the interplanetary phase of the acceleration (Table 1), and that while the nose of the shock from the Nov. 4 event passed close to Earth, in contrast the nose of the shock from the Nov. 6 event was significantly westward of Earth when it passed 1 AU. Cane et al. (1988) have shown that the west flank of shocks produce weak particle increases, as observed here for low energies during the second event.

The factor of 4 ^{3}He enrichment reported here is much lower than the expectation for impulsive events (factors of 1,000-10,000), and also shows no time variation, indicating that the acceleration history of these particles is similar to that of the other heavy ions. A puzzling aspect of the abundances observed here is the simultaneous enhancement of both low mass-to-charge ratio species (^{3}He) and high mass-to-charge ratio species (Fe) compared to reference elements ^{4}He and ^{16}O that have mass-to-charge ratio of ~2. This unexpected pattern might be related to other isotopic anomalies observed here (Leske et al. 1999).

The spectral hardening that occurs below a ~few MeV/n raises many interesting questions. Since shocks produce power law spectra, presumably near the Sun there was originally a single power law spectrum in the energy range well above the injection threshold Lee (1983), but by the time the particles reached 1 AU there was a depletion at low energies. This might be due to adiabatic deceleration, which would be more important for low energy particles. However, the opposite behavior, namely a hardening of the spectra at higher energies, has also been observed in the Nov. 22, 1977 SEP event Beeck et al. (1987). Clearly, additional observations will be required to understand this issue. For a more complete discussion of these events, see Mason et al. (1999).

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